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PARAMETRIC INVESTIGATION OF BRAYTON CYCLE FOR HIGH TEMPERATURE GAS-COOLED REACTORS

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ABSTRACT

The Idaho National Engineering and Environmental Laboratory (INEEL) is investigating a Brayton cycle efficiency improvement on a high temperature gas-cooled reactor (HTGR) as part of Generation-IV nuclear engineering research initiative.

In this project, we are investigating helium Brayton cycles for the secondary side of an indirect energy conversion system. Ultimately we will investigate the improvement of the Brayton cycle using other fluids, such as supercritical carbon dioxide. Prior to the cycle improvement study, we established a number of baseline cases for the helium indirect Brayton cycle. These cases look at both single-shaft and multiple-shaft turbomachinary. The baseline cases are based on a 250 MW thermal pebble bed HTGR. The results from this study are applicable to other reactor concepts such as a very high temperature gas-cooled reactor (VHTR), fast gas-cooled reactor (FGR), supercritical water reactor (SWR), and others.

In this study, we are using the HYSYS computer code for optimization of the helium Brayton cycle. Besides the HYSYS process optimization, we performed parametric study to see the effect of important parameters on the cycle efficiency. For these parametric calculations, we use a cycle efficiency model that was developed based on the Visual Basic computer language. As a part of this study we are currently investigated single-shaft vs. multiple shaft arrangement for cycle efficiency and comparison, which will be published in the next paper.

The ultimate goal of this study is to use supercritical carbon dioxide for the HTGR power conversion loop in order to improve the cycle efficiency to values great than that of the helium Brayton cycle.

This paper includes preliminary calculations of the steady state overall Brayton cycle efficiency based on the pebble bed reactor reference design (helium used as the working fluid) and compares those results with an initial calculation of a CO_2 Brayton cycle.

INTRODUCTION

The HTGR is a graphite-moderated, helium-cooled reactor using a direct or indirect gas cycle to convert the heat generated by nuclear fission into electrical energy by means of a helium Brayton cycle. Since the early 1950's the HTGR technology has been researched and some reactors were built. [1]. The HTGR works on the principle of flowing a coolant (gas) through the reactor core where it is heated to a high temperature and then flowing the high temperature gas directly to a steam generator or a gas turbine. These reactors have been built both in England and Germany. The Arbeitsgemeinschaft Versuchsreactok (AVR), 15-MWe-test reactor located at Forschungszentrum Juelich, Germany was constructed starting in 1961. Criticality was first achieved in 1966. The AVR was operated for 21 years. In 1974, the reactor outlet temperature was raised to 950°C, which was needed to test very-high-temperature nuclear process heat applications. The most recent Pebble Bed Reactor (PBR) built is the Chinese HTR-10 (10 MW), which first achieved criticality December 2000 [2-4].

The HTR-10 was designed to be operated up to 950°C for investigating diverse power generation systems (e.g., gas turbine) and nuclear process heat applications [5].

In the mid-1950s, interest in gas-cooled reactors was revived in the U.S., United Kingdom, France and Germany. Several of these reactors were built. Recently countries including the U.S, South Africa and the Netherlands [6,7] renewed their interest in gas-cooled reactor technology, particularly the modular pebble bed reactor concept.

The only commercial HTGR built in the US was the Fort St. Vrain unit, located at the confluence of the St. Vrain Creek and the South Platte River near Platteville, Colorado. In June 1968 construction began and the initial criticality was reached on January 31 1974 [1]. This plant was operated with some technical problems and eventually it was shut down due to water loss in water-cooling bearing on the circulator, which cannot be a problem now thanks to the improvement of the circulator design.

Recently Eskom, a power company based in South Africa, submitted a nuclear installation license application to the National Nuclear Regulator (NNR). It is proposed to locate the installation on Eskom property within the owner-controlled boundary of Koeberg Nuclear Power Station located in the Western Cape. In the U.S., the DOE plans to build a VHTR at the INEEL site by 2016.

REFERENCE DESIGN

Figure 1 shows the reference design developed at MIT [8] for the pebble bed reactor (PBR). An intermediate heat exchanger (IHX) is used to couple a PBR to a Brayton cycle.

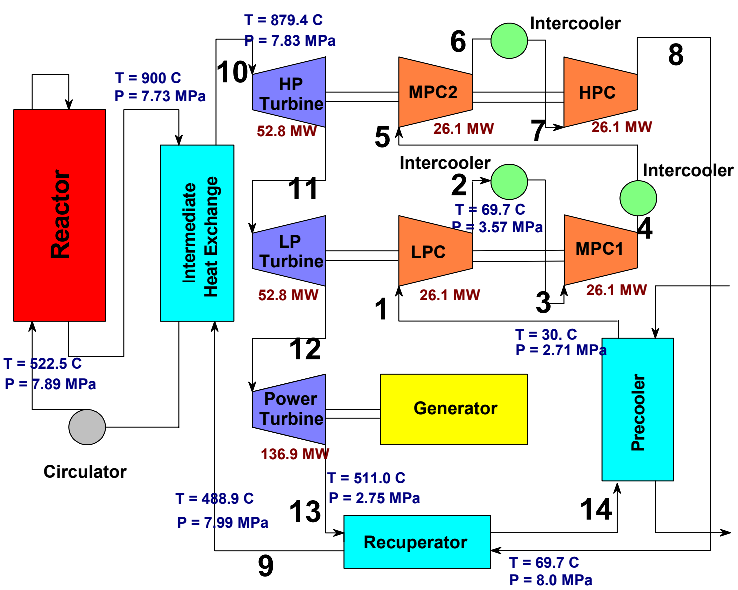

Figure 1. Schematic of Reference HTGR Design

In the primary system, the helium is heated to 900°C in the pebble bed reactor and then enters the primary side of the IHX, in which the heat is transferred to the power conversion unit.

The helium flowing out from the primary side of the IHX is compressed in the circulator up to 7.89 MPa. Thereafter most of the helium is delivered back to the channels of the side reflector in the core while a small part is bled into the primary side of the vessel cooling heat exchanger.

The helium in the primary side of the vessel cooling heat exchanger is cooled to a low temperature, and then flows upward through the annulus between the core barrel and reactor pressure vessel (RPV) to cool the RPV. Finally, the helium from the channels in the side reflector and RPV mix in the core upper plenum, then flows into the core, completing a circulation loop.

In the power conversion unit, the helium coming from the secondary side of IHX enters the high-pressure turbine at a temperature of 879.4°C. After sequential expansion in the high-pressure, medium-pressure, low-pressure, and power turbines, the helium enters the low-pressure side of the recuperator and transfers its heat to the high-pressure side helium. The helium then rejects more heat to a precooler, exiting the precooler at 30°C. The helium is then compressed in a low-pressure compressor to an intermediate pressure, and then it flows through intercoolers where it is again cooled to 30°C. This process is repeated several times until the helium stream exits the high-pressure compressor at 8.0 MPa. Most of the helium with a pressure of 8.0 MPa is discharged into the high-pressure side of the recuperator, where it recovers the exhaust heat from the power turbine. A small part of the helium is delivered to the vessel cooling heat exchanger to cool the helium of the primary system. The helium from the high-pressure side of the recuperator and the helium from the primary side of vessel cooling heat exchanger mix before they enter the secondary side of the IHX, at which point the helium starts the next circulation.

The reference design for a three- shaft turbomachinary as shown in Figure 1 is based on a 250 MW thermal reactor with helium circulated in both the primary and secondary side of the HTGR. We made preliminary investigations on a single-shaft vs. multiple-shaft turbomachinary however, in this paper we will presents only results from three-shaft turbomachinary arrangement.

CYCLE EFFICIENCY CALCULATION

Figure 2 depicts a temperature-entropy (T-S) representation of the reference Brayton cycle using helium as the working fluid.

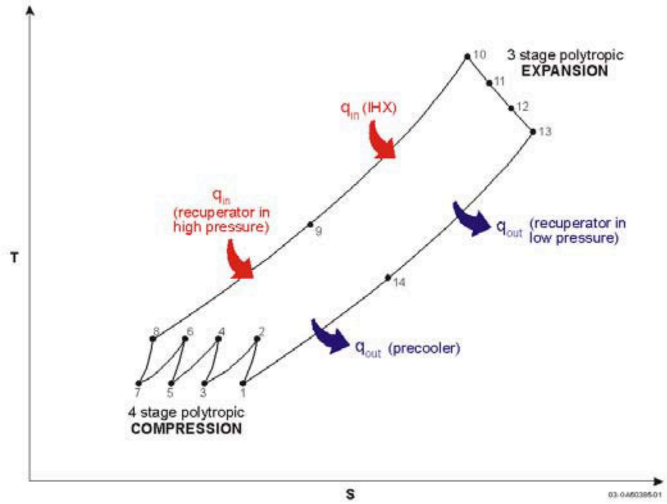

Figure 2. T-S diagram for the PBR reference design in the power conversion side.

Points 1 to 8 are associated with a 4-stage compression of the helium from the inlet (1) of the low-pressure compressor (LPC) to the outlet (8) of the high-pressure compressor (HPC). The helium then flows to the inlet of the intermediate heat exchanger (9) via the high-pressure side of the recuperator. Heat is then added to the helium gas in the intermediate heat changer. The helium then experiences a sequence of expansions through 3 turbines (points 10 to 13) and then some of the remaining exhaust heat is transferred (point 14) to the cold side stream of the recuperator. The helium stream then exits the recuperator flows through the precooler where it is cooled further before entering LPC.

As shown in the T-S diagram, the compression and expansion processes are irreversible adiabatic processes thus resulting in an increase in the entropy.

The thermal efficiency with polytropic compression and expansion is defined as [9]:

$$\eta_{th} = \frac{m_{10}(h_{13} - h_{10}) - m_1(h_2 - h_1) - m_3(h_4 - h_3) - m_5(h_6 - h_5) - m_7(h_8 - h_7)}{m_{10}(h_{10} - h_9)} \quad (1)$$

or the overall plant busbar efficiency is expressed as:

$$\eta_{busbar} = \frac{W_T \eta_{gen} - W_{cir}/\eta_{motor} - W_s}{Q_{th}} \quad (2)$$

where W_T is the power turbine output power, η_{gen} is the generator efficiency, W_{cir} is the circulator input power, η_{motor} is the motor efficiency, W_s is the stationary loads, and Q_{th} is the reactor thermal power. For the efficiency calculations, we used the busbar efficiency, which is more conservative than the thermal efficiency.

RESULTS

Important parameters for improving the Brayton cycle efficiency are reactor core outlet temperature, efficiencies of the compressors, turbines, intermediate heat exchanger, and others. In this study the reactor core outlet temperature was varied between 850°C and 1000°C. For each of the fixed outlet temperatures (850°C, 900°C, 950°C 1000°C), the inlet temperature to the core was varied between 400°C and 640°C. The results are also based on a three shaft arrangement for the helium Brayton cycle, using an intermediate heat exchanger effectiveness factor of 92 percent, a 90 percent polytropic efficiency for the compressors and turbines, and a 30 degree Celsius cooling temperature to the precooler and the three intercoolers.

The mass flow rate through the core needed to remove 250 MW of thermal energy from the reactor core is a function of the required temperature rise across the core. Thus, the pressure drop across the core is a function of the core mass flow rate which in turn affect the amount of work require to drive the circulator. Previously we did not account for the effect of the pressure drop on the Brayton cycle efficiency. For these calculations, we used the pressure drop equation shown below that is used to model the pressure drop through a pebble bed reactor.

The friction pressure drop ΔP_f through a pebble bed of height H can be expressed as

$$\Delta P_f = \psi \cdot \frac{H}{d_h} \cdot \frac{\rho_{ave}}{2} \cdot U_p^2 \quad (3)$$

$$\psi = \frac{320}{\frac{Re}{1-\varepsilon}} + \frac{6}{\left(\frac{Re}{1-\varepsilon}\right)^{0.1}} \quad (4)$$

where ψ is the pressure drop coefficient, H is the height of the core, d_h is the hydraulic diameter, ρ_{ave} is the average density of the fluid in the core, U_p is the mean velocity in the gaps between the particles, Re is Reynolds number, and ε is the porosity of pebble bed.

The new numerical model was benchmarked against a three-shaft baseline case based on HYSIS simulation (version 2.2.2) [10]. The results and comparison are shown in Table 1.

Table 1. Comparison between HYSIS simulation and Visual-Basic (V-B) based model.

	HYSIS simulation	V-B Model
Inlet temperature / pressure to HP turbine	865^0C / 746 MPa	864^0C / 746 MPa
Outlet temperature / pressure to HP compressor	74.5^0C / 7.9 MPa	77.5^0C / 8.0 MPa
Total 4 compressor work	111.7 MW	112.7 MW
Total 3 turbine work	129.5 MW	129.9 MW
Busbar efficiency	47 %	46 %

Figure 3 shows a three-dimensional plot of the plant busbar efficiency as a function of reactor inlet and outlet temperatures for a three-shaft 250 MW thermal helium Brayton cycle using a 92 percent effectiveness factor for the intermediate heat exchange and 90 percent polytropic efficiency for the turbines and compressors.

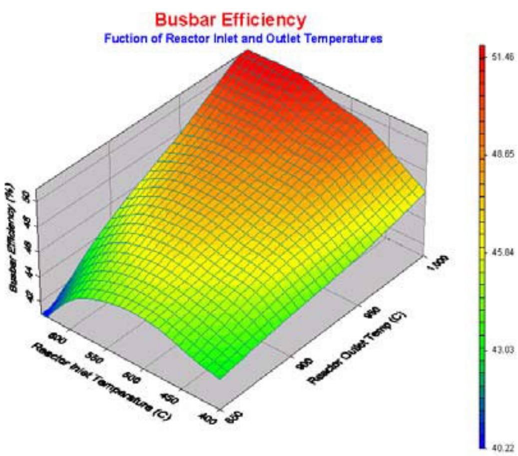

Figure 3. Busbar efficiency as a function of reactor inlet and outlet temperatures.

The results show that at a relative low reactor outlet temperature (850°) the maximum cycle efficiency peaks at 45%, which corresponds to a reactor inlet temperature of 520°C. As the reactor outlet temperature is allowed to increase, the maximum efficiency increases to 51.5% at an outlet temperature of 1000°C. The maximum efficiency for this case occurs for a reactor inlet temperature of 640°C. For intermediate outlet temperature between 850°C and 1000°C the cycle efficiency increase from 45% to 51.5% with the corresponding reactor inlet temperature increasing from 520°C to 640°C.

We investigated the effect of compressor efficiency on the overall Brayton cycle efficiency by varying the compressor efficiency from 90 to 94 percent as shown in Figure 4. The reactor outlet temperature was held at 900°C for the three compressor efficiencies.

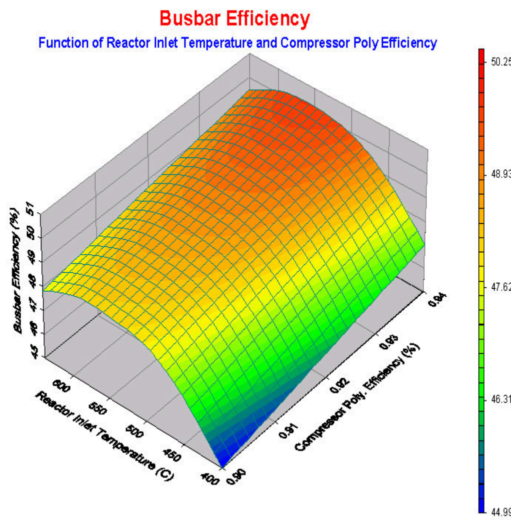

Figure 4. Busbar efficiency as a function of compressor efficiencies and reactor inlet temperatures.

The results presented in Figure 4 show that the cycle efficiency increases from 48.2% for a compressor polytropic efficiency of 90% to 50.2% for a polytropic efficiency of 94%. The maximum efficiencies all occurred at a reactor inlet temperature of 550°C.

A practical way of reducing the compressor work is to keep the specific volume of the gas as small as possible during the polytropic compression. This is achieved by maintaining the temperature of the gas as low as possible because specific volume is proportional to temperature. By dividing the compression process into stages and cooling the gas between stages, the total work done during the compression process is reduced. By reducing the compressor inlet temperature by 1°C, the overall cycle efficiency increases by 0.2 percent as shown in Figure 5.

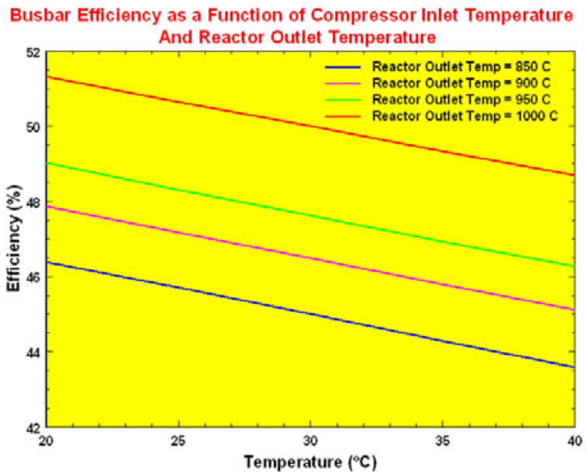

Figure 5. Busbar efficiency at various cooling temperatures.

We also investigated the sensitivity of the effectiveness of intermediate heat exchanger (IHX) on the overall busbar efficiency. If the effectiveness of IHX is improved from 90% to 92% at a core outlet temperature of 950^{0}C and a core inlet temperature of 400^{0}C, for example, there is an initial improvement of the overall Brayton efficiency by 0.65%. The IHX effectiveness has less impact on the efficiency compared to the compressor efficiency.

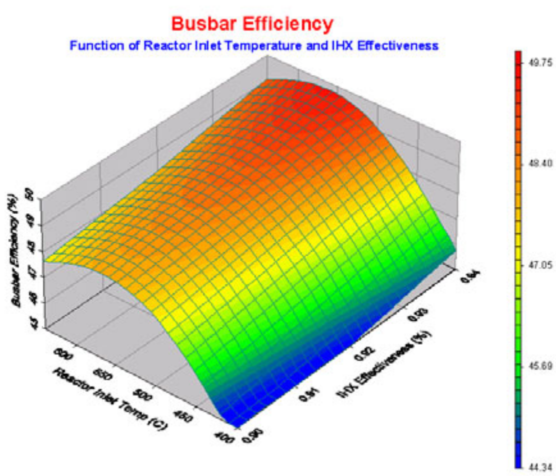

Figure 6. Busbar efficiency as a function of IHX efficiencies and reactor inlet temperatures.

Figure 7 shows how the temperature difference across the reactor impacts the power turbine inlet temperature that is very important to the overall efficiency. All other detailed calculations of efficiency dealing with the pressure ratios and other important parameters will be reported in great details in the annual reports.

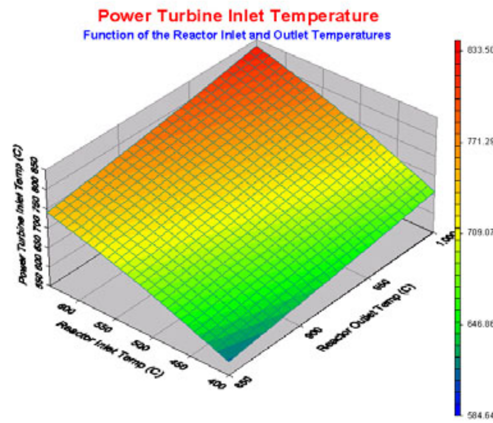

Figure 7. Power turbine inlet temperature as a function of temperature drop across the reactor.

We made preliminary CO2 Brayton cycle and compared with that of the reference design (reactor outlet temperature of 900^{0}C) parameters shown in Table 2 below.

	REFERENCE DESIGN with Helium	HYSYS with SC CO_2
Heat Exchanger Outlet	879.4°C	814.6^{o}C
	7.83 MPa	7.98 MPa
HP Turbine Outlet	799.2°C	735.5^{o}C
	6.44 MPa	4.67 MPa
LP Turbine Outlet	719.0°C	714^{o}C
	5.21 MPa	4.016MPa
Power Turbine Outlet	511.0°C	535.1^{o}C
	2.75 MPa	1.034 MPa
Recuperator Outlet LP	96.1°C	151.8^{o}C
	2.73 MPa	1.014 MPa
Precooler Outlet	30.0°C	30^{o}C
	2.71 MPa	0.9942 MPa
LP Compressor Outlet	69.7°C	57.16^{o}C
	3.57 MPa	1.407 MPa
Intercooler1 Outlet	30.0°C	30.0^{o}C
	3.54 MPa	1.377 MPa
MP1 Compressor Outlet	69.7°C	34.87^{o}C
	4.67 MPa	1.467 MPa
Intercooler2 Outlet	30.0°C	30.0^{o}C
	4.63 MPa	4.62 MPa
MP2 Compressor Outlet	69.7°C	70.2^{o}C
	6.11 MPa	6.11 MPa
Intercooler3 Outlet	30.0°C	30.0^{o}C
	6.06 MPa	6.06 MPa
HP Compressor Outlet	69.7°C	67.3^{o}C
	8.00 MPa	7.87 MPa
Recuperator Outlet HP	488.9°C	488.8^{o}C
	7.99 MPa	7.99 MPa

Vol. Flow of gas	3,676 m^3/h	3,012 m^3/h
Busbar efficiency	47%	53%

Table 2. Temperature and pressure comparisons from the reference design between the reference design and a preliminary case of CO_2 Brayton cycle.

CONCLUSION

The preliminary results indicate that the PBR plant busbar efficiency was improved by using the high pressure CO_2 gas in the power conversion. The improvement is attributed to less work due to the reduced volumetric flow in the sequence of compressors compared to the compressor work with helium gas in the power conversion unit. Parametric investigation from this study indicates how much busbar efficiency can be improved by improving each component's efficiency.

ACKONOWLEDGEMENT

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